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Design considerations and performance of BGO Compton suppression shields

G Stam

Engelhard De Meern B V, P O Box 19, 3454 ZG De Meern, The Netherlands

Abstract : The performance of bismuth germanate oxide (BGO) crystals for Compton suppression shields is described. BGO is a high density scintillator very suitable for the detection of gamma-rays. BGO Compton suppression shields are used together with large volume germanium detectors in large spectrometer arrays. This combination opened a new field of gamma-ray spectroscopy because of a significant improvement in signal to noise ratios. Design considerations for various BGO crystals for Compton suppression shields are reviewed.

Keywords : BGO crystals, Compton suppression shields, light yield.

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1. Introduction

Germanium detectors surrounded by Compton suppression shields consisting of Bismuth Germanate Oxide (BGO) and Sodium Iodide Thallium activated (NaI(Tl)) are applied in several experiments like Hera, Politessa, Nordball and Osiris. The design of future projects like e.g. Gamic and Euroball makes a renewed discussion about the performance of BGO Compton suppression shields worthwhile.

The most fundamental characteristic of a germanium detector used for multiple gamma coincidence measurements is the peak to total ratio (P/T) expressed as the ratio of the counts in the full energy peak to the total counts in the spectrum. For a 1 MeV gamma-line typical values for the (P/T) ratio is 15-20% for a bare Ge-detector. Using a Compton suppression shield, this value improves to 50-60%.

The useful events in a multiple coincidence measurement can be expressed by

$$F=(P/T)^N$$

where F is the fraction of useful events and N is the gamma-ray multiplicity (1). This means that e.g. for $N=4$ and using detectors with a (P/T) of 60 %, only 13 % of the events is useful. The remaining part consist of undesirable background. From these figures it becomes quite clear that higher multiplicity studies are impossible if no better P/T ratio's can be achieved. Better P/T ratio's can be achieved by :

The text and the references are printed according to the author's style.

—larger Ge-detectors with better P/T ratio's

—the design of better Compton suppression shields

In the past also asymmetric designs were used by Lieder *et al* (2), but mechanical constrains together with performance considerations made the choice for symmetric designs favorable.

The choice of solely BGO instead of BGO with NaI(Tl) as the scintillation material in the cone of the Compton suppression shield has several reasons. In the first Compton suppression shields (Lieder, Nolan see Figure 1) (2, 3) NaI(Tl) was

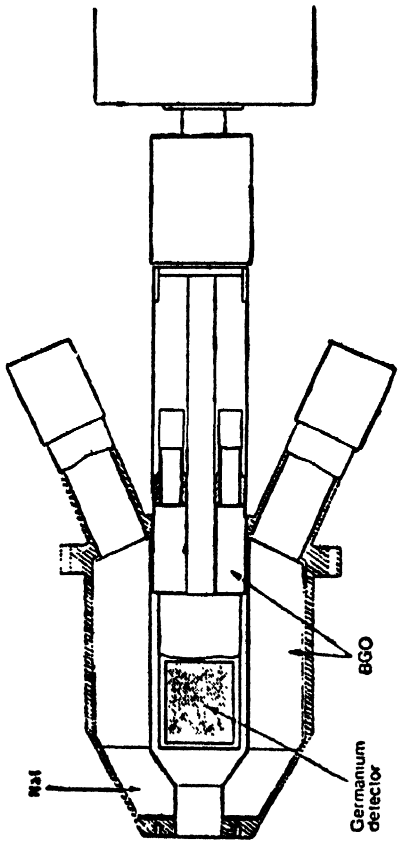

Figure 1. The Liverpool design of a BGO Compton suppression shield with a NaI (Tl) cone for a Ge-detector placed in the center. Eight photomultiplier tubes are mounted on the back of the BGO.

applied for the cone of the shield. At that time the optical quality of BGO crystals was not good enough to transfer the light from the cone to the photomultiplier to detect low energy ($<$ 200 keV) gamma-rays absorbed in the cone.

Because of the higher light output of NaI(Tl), this material was able to detect and give sufficient light output for suppression of these energies. The disadvantage of the NaI(Tl) is that it is hygroscopic. This makes a hermetic sealing necessary introducing extra scattering material in the shield, especially the optical window between the NaI(Tl) and the BGO. A second disadvantage was that due to the different light output of the two materials it was not possible to use the Compton suppression shield as an adding back detector to recreate the full energy peak.

The now-a-days much better quality of BGO crystals permits to use solely BGO crystals for Compton suppression shields.

Scope of this study

The objective of the measurements was to find the best way to optically threat BGO crystals for use in Compton suppression shields. The two parameters of primary interest were the uniformity of light output along the length of the crystal and the total light output.

Light collection in BGO :

BGO scintillation crystals are very attractive detectors for gamma-rays due to their high density. However the intrinsic light output is up to 10 times less for BGO than for NaI(Tl). For this reason it is clear that great care must be taken to ensure that the largest possible fraction of the light emitted is detected by the photomultiplier tube.

The problem one encounters here is the high refractive index of the BGO ($n=2.15$). This implies a critical angle of reflection of 44°. This has the conse-

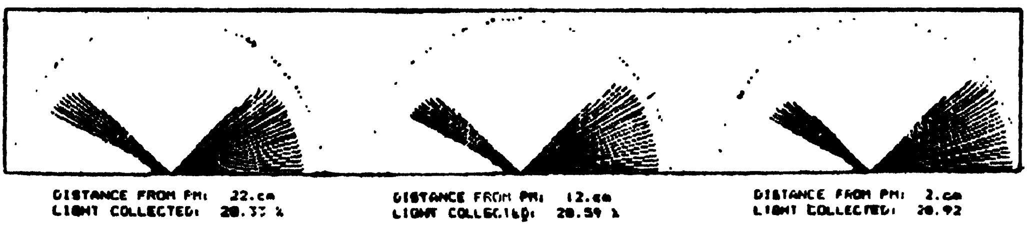

Figure 2(a). Emitted light for BGO as a function of the distance from the photomultiplier tube. Crystal dimensions 24 * 2 * 2 cm.

quence that light can be trapped very easily by total internal reflections so reducing the fraction of the scintillation light detected.

Let us first consider a crystal with sizes 240 × 20 × 20 mm and an absorbtion of 10% over 20 cm. We assume no reflector surrounds the crystal and all sides are optically polished. The diagram of Figure 2a (4) shows the calculated distribution of light output as a function of the emission angle. For each angle a point representing 100 % efficiency is plotted, together with a vector. The length of which is proportional to the percentage of light collected. It is clear there is a first sector for which the light is very well detected (angle < 44°). If the angle of emission related to the front face is greater than 44° the light is trapped in the crystal.

The second sector of light rays going first to the rear face can be separated in two parts, one part is in total reflection at the rear face and therefore very well detected on the front face. The second part is not totally reflected and therefore lost. Note the very good uniformity in this case.

Tapered crystals :

For tapered crystals the problem is more complex, because the shape of the crystal introduces more non uniformity. Let us take for this example a crystal measuring 240×30×30 mm tapered to 20×20 mm. Figure 2(b) shows the light output in

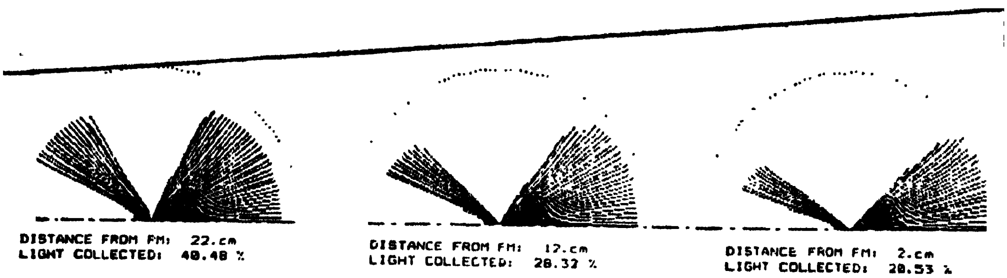

Figure 2(b). As figure 2(a) but crystal dimension 24 * (3*3) * (2*2) cm.

tha same way as Figure 2(a). The figure shows that the acceptance sector is larger for the light emitted from the far end, because after some reflections on the lateral faces the light rays come closer to the axis of the crystal. Note the large non uniformity from 20.53 % light collection at 2.5 cm to 40.48 % at 22 cm.

Uniformity :

To get a better uniformity it is necessary to increase the light output near the front face or decrease it near the end face. To investigate the optimal way to achieve this, the measurements described below were performed.

2. Experimental

For the measurements a set of 10 BGO crystals were used for one Compton suppression shield. Each of the 10 crystals are slightly different in shape, but could be considered as five pairs because one crystal is the mirror image of the other (e.g. 1A is the mirror image of 1B). The numbering of the crystals in the Compton suppression shield is shown in Figure 3.

The uniformity of the light output throughout the crystal was measured by placing a collimator with a ^{137}Cs (662 keV) source at different positions along the crystal (Figure 4) and measuring the PMT output. The PMT used is a Hamamatsu type R434 with 1 1/8″ diameter. The PMT was coupled with silicon grease to the crystal. The PMT signal was fed into a charge sensitive preamplifier and amplified by a spectroscopy amplifier. The spectrum was analyzed by a Nucleus Personal Computer Analyzer.

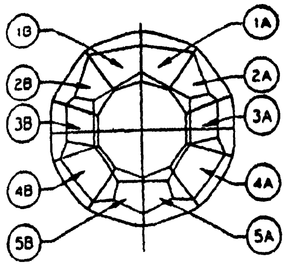

Figure 3. End view of the Compton suppression shield, with labeling scheme.

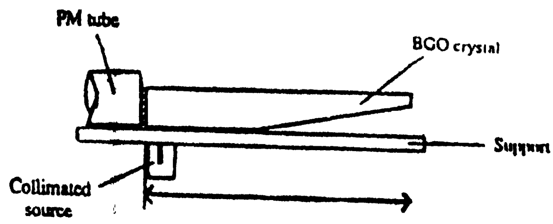

Figure 4. Schematic diagram of measurement setup.

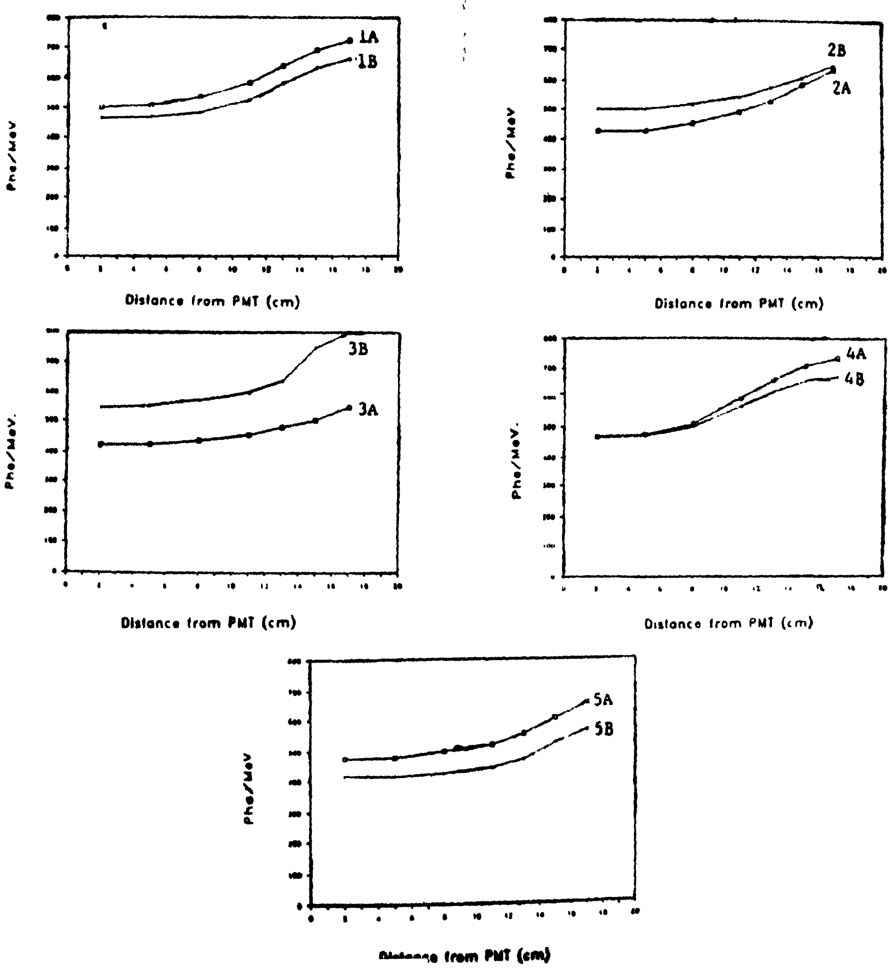

Figure 5. Photoelectron output per MeV for five pairs as a function of the distance to the photomultiplier tube. All crystals were polished, and wrapped in reflective paper.

By recording the channel number of the 662 keV peak from the 137 Cs source, the amount of light emitted at that specific point can be determined. This value was converted to photo-electrons/MeV (appendix 1). Using this unit one is undependable of amplifier gain and source energy making it easier to compare measurements taken under different circumstances.

3. Measurements

Polished crystals :

Figure 5 shows the result for the first five pairs. At this stage the crystals were totally optically polished and wrapped with HR-15 reflective paper and two layers

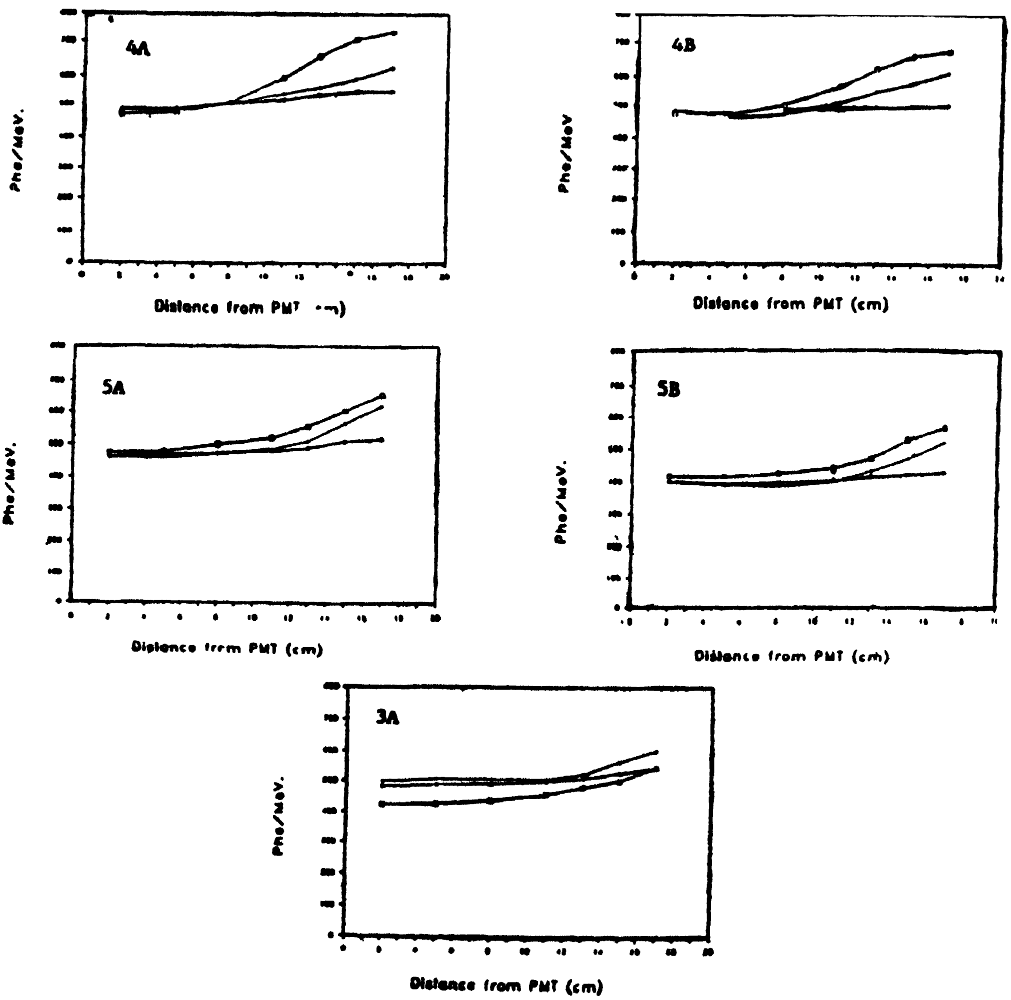

Figure 6. Photoelectron output per MeV as a function of the distance to the photomultiplier, for crystals as labelled, with □ polished (uncompensated), + compensated once and ◇ compensated twice.

of aluminum type. All crystals show the expected trend : higher light output from the far end. The crystals show a non uniformity ranging from 24 % to 45%.

Compensated crystals :

The next step was to take the first five pairs and try to improve the non uniformity. This should be done in such a way that the average light output is still as high as

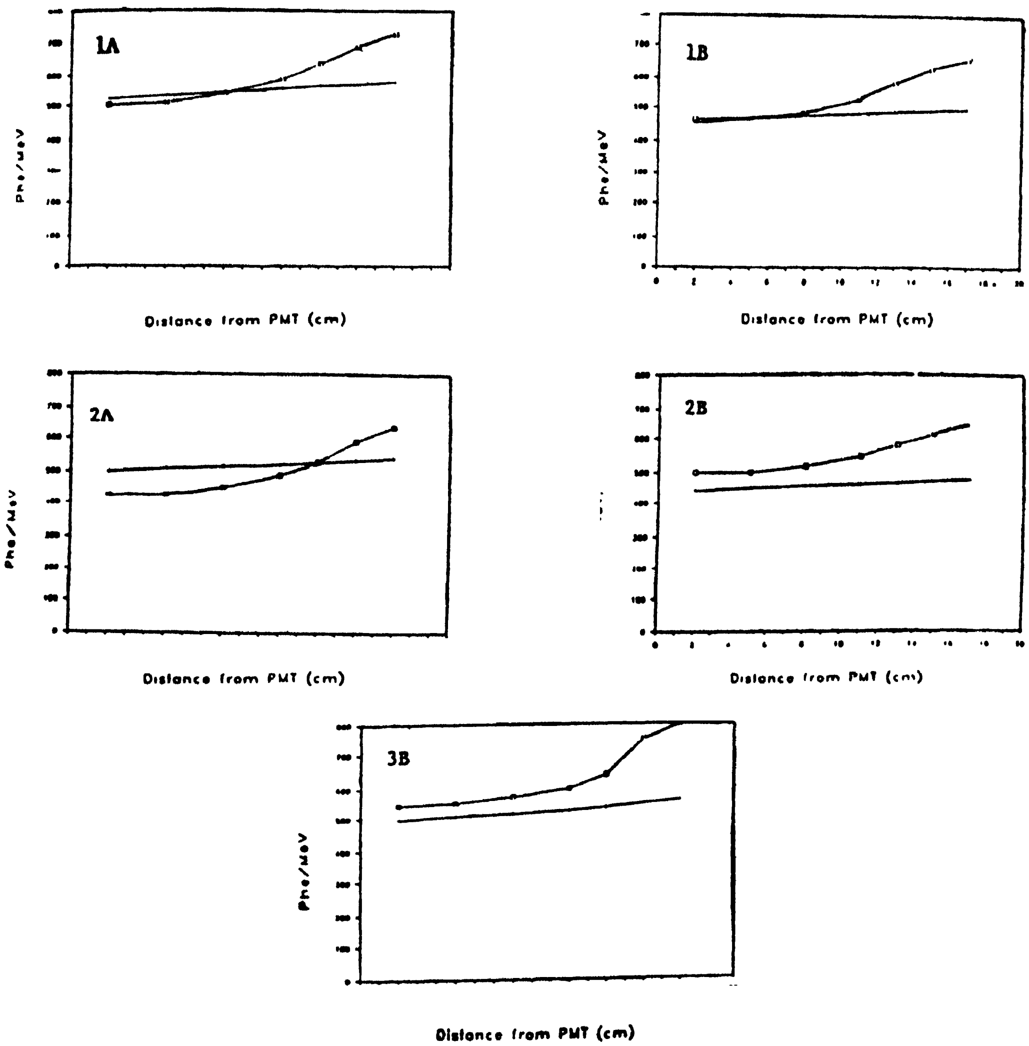

Figure 7. Photoelectron output per MeV as a function of the distance to the photomultiplier for five crystals. □ polished (uncompensated) + compensated once.

possible and the light output is constant along the length of the crystal. If a crystal shows non uniformity this crystal will have a worse energy resolution than a crystal which has a uniform behaviour.

Figure 6 shows the result after one and two compensations for the crystals as labelled. The remainder of the crystals is shown in Figure 7. These crystals have only been compensated once using the experience gained during compensation of the first five crystals.

Compensation is basically roughing up parts of the crystal. This has the effect that the light is diffused reflected. The diffusion takes care the light is not hitting the crystal surface each time under the same angle and so, after sufficient many reflections, the photon will eventually come out. The final fraction detected will be determined by competition between the following :

—detection in the PMT

—absorbtion in the volume of the crystal

—absorbtion at the reflector

As explained before, the objective is to achieve the good uniformity by increasing the light output from the points giving the lowest light output. It is clear from the graphs that the good uniformity can be achieved only by decreasing the

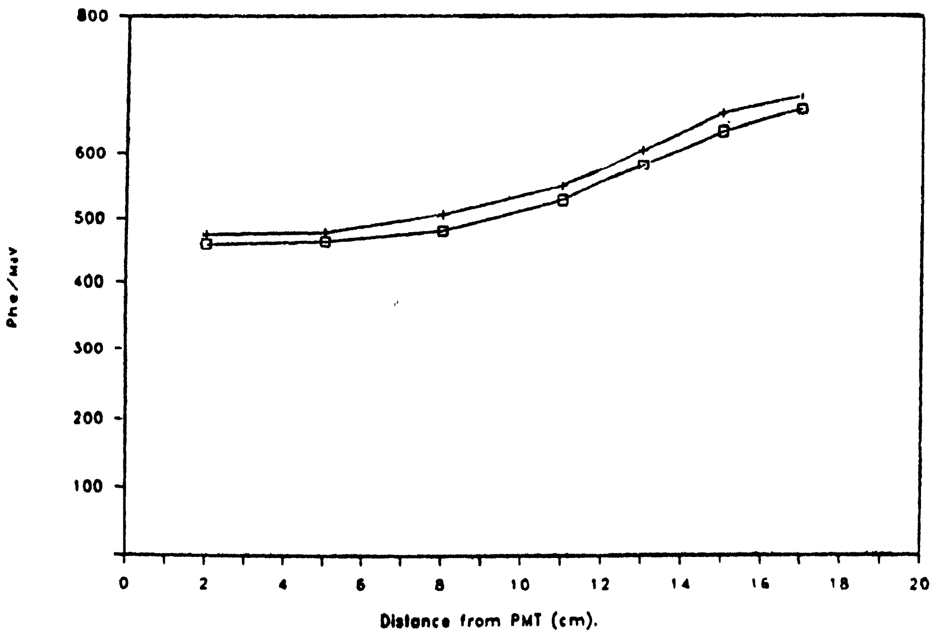

Figure 8. Photoelectron output per MeV as a function of the distance to the photomultiplier for crystal 1B, with measurements taken on consecutive days, □ on day 1 and + on day 2.

light output. This means that the total light output is reduced (=total area under the curve), in some cases up to 20 %. The achieved uniformity is typically 9.7 %, with 5.5 % as the best result and 12.6 % as the worst.

There are two exceptions crystals 2A and 3A. Here the compensation raised the total light output. However when we look at the crystals labelled 2B and 3B (the mirror types) we see the same behaviour as for the rest of the crystals. This justifies the conclusion that the light output when the crystal was polished has been underestimated, probably due to a bad coupling between PMT and crystal.

Reproducibility :

An indication of the reproducibility of the measurements taken was obtained by measuring the same crystal (1B) on two consecutive days. The results are shown in Figure 8. Changes in the crystals temperature (temperature coefficient for BGO is – 1.5 %/K) and the reproducibility of the coupling between PMT and crystal are probably the reason for the difference of 3.6% compared to the previous measurement. This is because the shape of the curve remains the same except that a displacement exists.

Reflector :

As explained in the sections before, the scintillation light produced is internally reflected for a great part at the polished surfaces. The use of a reflector surrounding the crystal reduces the loss of light escaping from the crystal. As can be seen

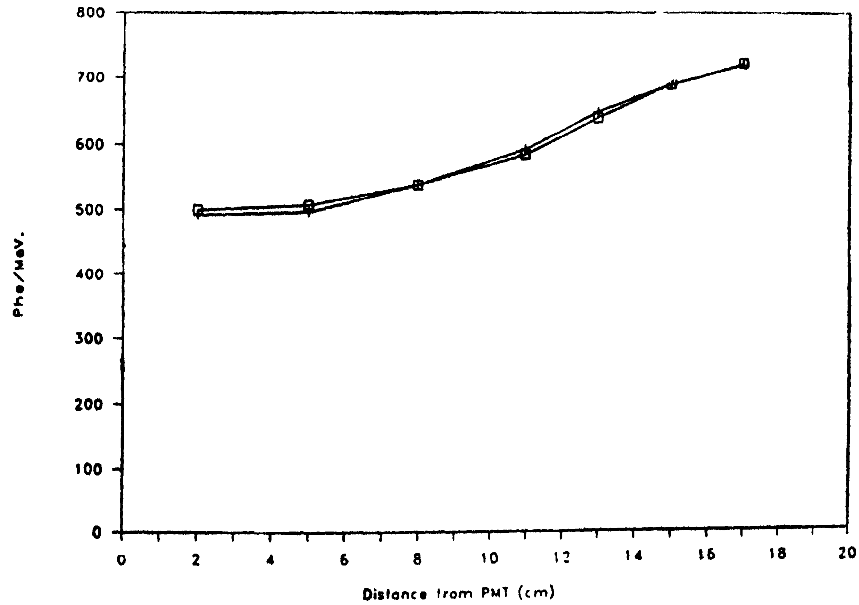

Figure 9. Photoelectron output per MeV as a function of the distance to the photomultiplier for crystal 1B in different reflectors, with □ HARSHAW reflector paper (HR – 15) and + teflon.

from Figure 9, using teflon instead of the Harshaw reflective paper (HR-15) has no significant effect on the total light output. The HR-15 will be used as reflector in the Compton suppression shields for the BGO crystals.

Uniformity as function of energy :

To check the uniformity for different energies, ^{137}Cs and ^{57}Co were used. In order to check whether the uniformity for this type of crystals depend on the point where the light is generated. Whereas the 662 keV from ^{137}Cs is for 90 %

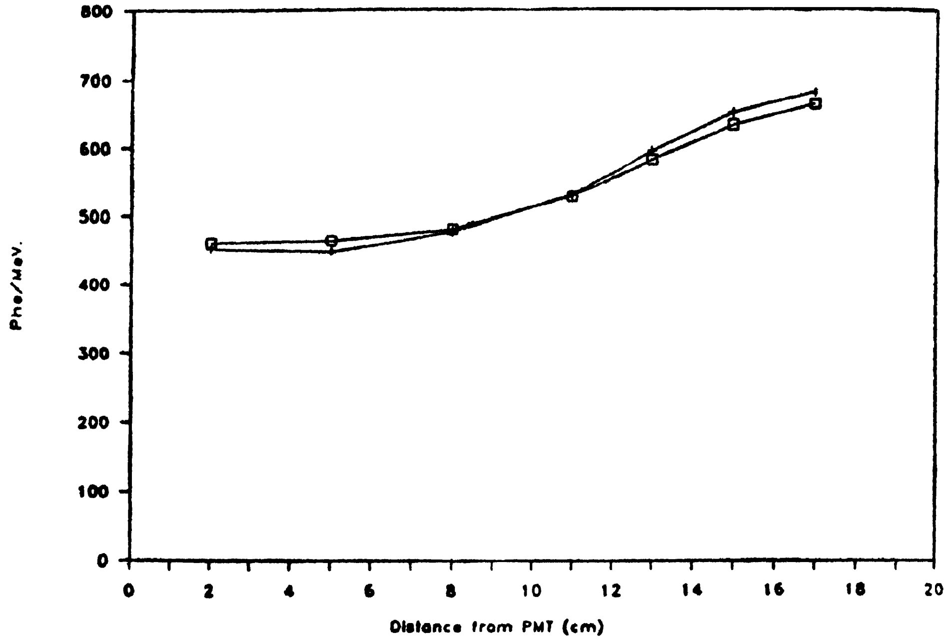

Figure 10. Photoelectron output per MeV as a function of the distance to the photomultiplier when different radiation sources were used, with □ ^{137}Cs (662 keV) and + ^{57}Co (122 keV).

absorbed in 40 mm BGO, the 122 keV from ^{57}Co is absorbed in 1.5 mm. Crystal 1A was measured with both sources. The results are shown in Figure 10. From the figure we can conclude that the uniformity is independent of the energy for this crystal size.

4. Conclusion

It has been shown that BGO crystals for Compton suppression shields can be compensated to a uniform lighr output. This at the cost of a total integrated light yield which is up to 20 % lower in some cases.

Measurements are planned with identical Compton suppression shields with totally polished and compensated crystals to determine the effect of the light output on the suppression.

Appendix I.

$$\text{Phe/MeV} = \frac{G}{G_{BGO}} * \frac{GP}{SPP} * \frac{1}{\text{Source energy}} \text{ (MeV)}$$

G = amplifier gain without BGO crystal present.

G_{BGO} = amplifier gain with BGO crystal present.

GP = channel number of peak in the spectrum with source and crystal.

SPP = channel number of single photon peak.

The single photon peak is the peak in the spectrum where the minimum amount of light (one photon) gives one photoelectron from the photocathode of the PMT. With the PMT in the dark and no BGO crystal present, the noise in the PMT will result in the single photon peak.

References

1. M. Moszynski, J. H. Bjerregard, J. J. Gaardhoje, B. Herskind, P. Knudsen and G. Sletten, 1989 *Nucl. Instrum. Meth.* **A280** 73-82
2. R. M. Lieder, H. Jäger, A. Neskakis, T. Venkova and C. Michel, 1984 *Nucl. Instrum. Meth.* **220** 363-370
3. P. J. Nolan, D. W. Gifford and P. J. Twin 1985 *Nucl. Instrum. Meth.* **A236** 95-99
4. C. Laviron and P. Lecoq *Cern/EF/0066e/PI/CL/fv* Cern report